The Silicon Vertex Detector of the Belle II Experiment

Yuma Uematsu (UTokyo) on behalf of the Belle II SVD group

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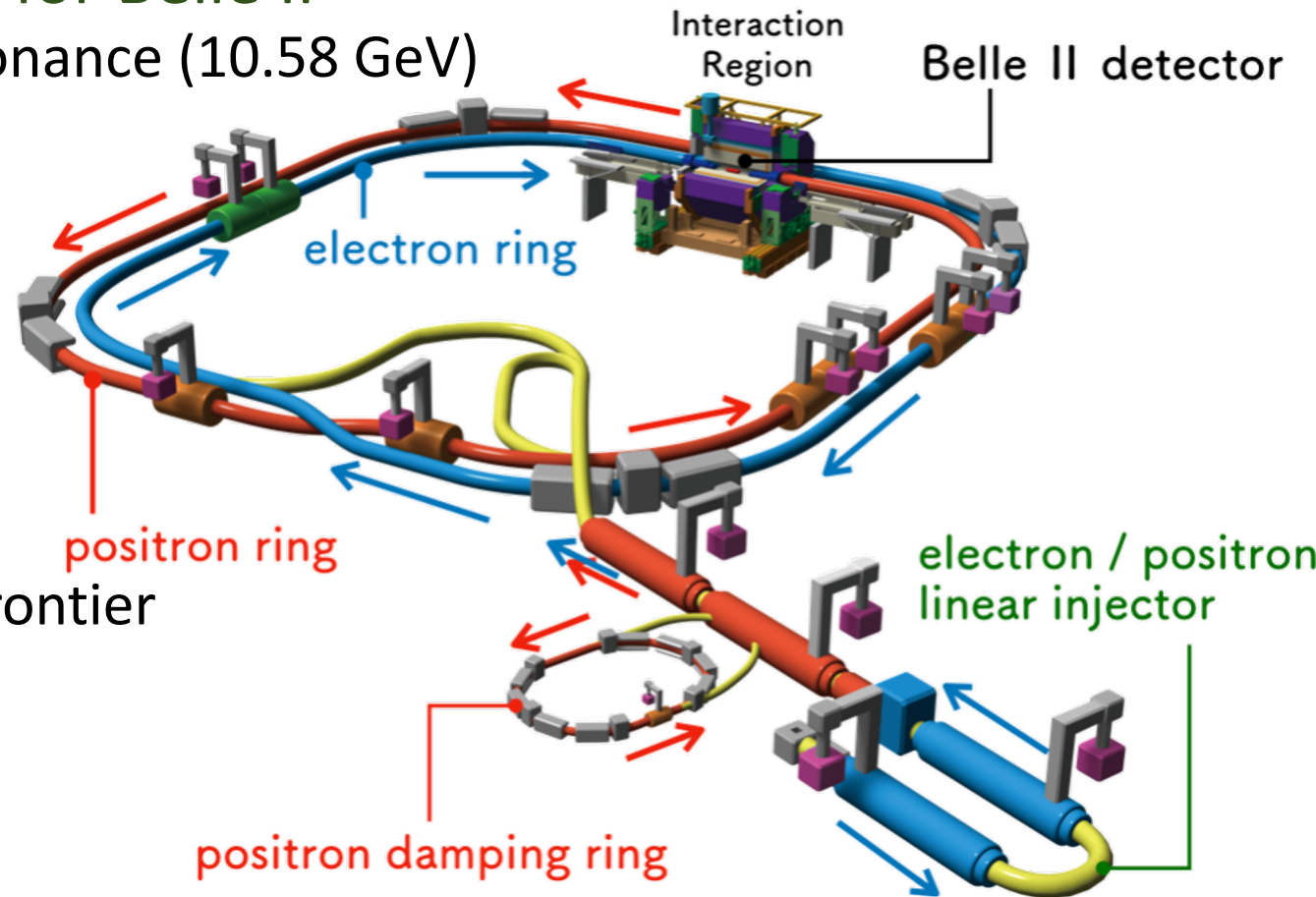# Outline

◆Introduction

◆Operation & Performance

◆Beam background & Radiation effect

◆Conclusions

Introduction

Belle II/SuperKEKB

◆ **SuperKEKB: dedicated accelerator for Belle II**

- Asymmetric e^+e^- collisions at Υ(4S) resonance (10.58 GeV)
- Target integrated luminosity: 50 ab^{-1}
- Target instantaneous luminosity: $\sim 6 \times 10^{35}$ $cm^{-2}s^{-1}$
- Current record: 3.1×10^{34} $cm^{-2}s^{-1}$

◆ **Belle II**

- New physics search at the luminosity frontier
- Accumulated 213 fb^{-1} data
- Essentials for physics programs:
  - Precise determination of decay vertices
  - Low momentum tracking
  - Good particle identification
  → Vertex Detector plays an important role

Belle II Vertex Detector

◆ **Requirements**
- Better vertex resolution than Belle to compensate reduced Lorentz boost
  - improved point resolution/reduced inner radius/lower material
- Operate in high background environment
  - Hit rate: 3 MHz/cm^2 @ SVD layer-3
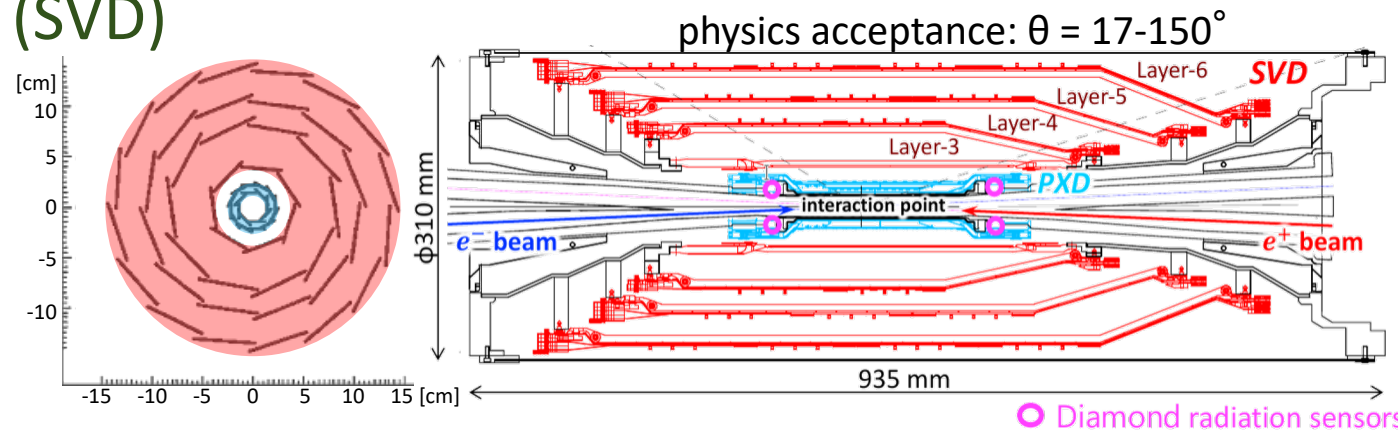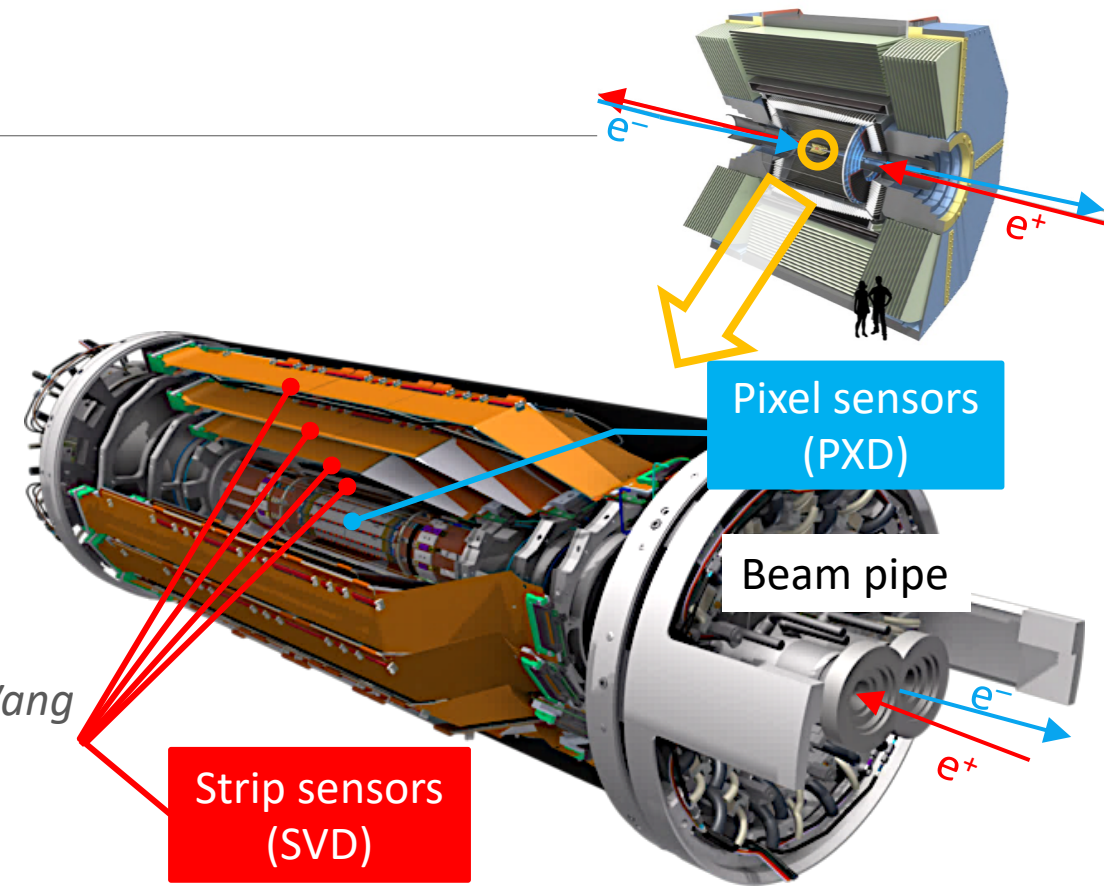- Radiation hard
  - 0.2 Mrad/yr. @ SVD layer-3

◆ **Layers-1-2: Pixel Detector (PXD)** → *talk by Boqun Wang*
- DEPFET pixel sensors
- Innermost layer 1.4 cm from interaction point

◆ **Layers-3-6: Silicon Vertex Detector (SVD)**

◆ **Diamond sensors**
- For radiation monitor and beam abort

Pixel sensors (PXD)

Beam pipe

Strip sensors (SVD)

physics acceptance: θ = 17-150°

Belle II Silicon Vertex Detector (SVD)

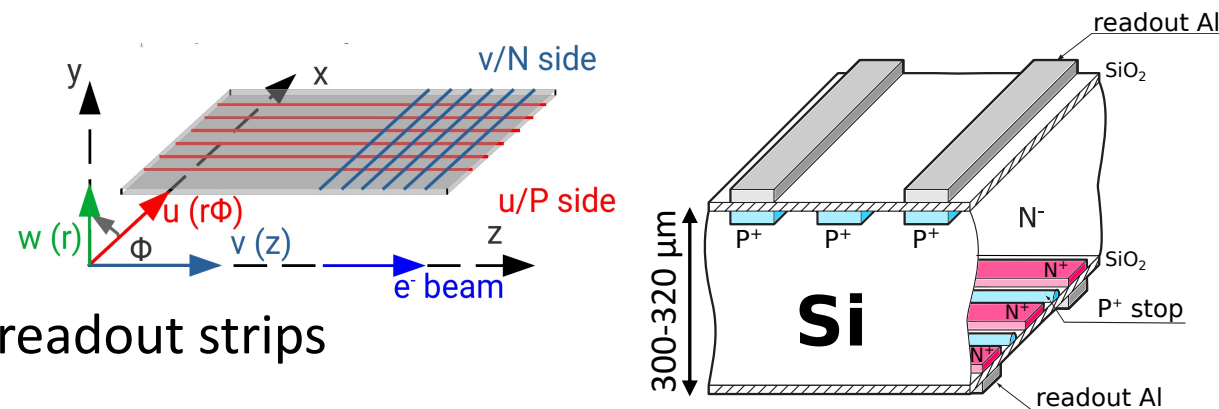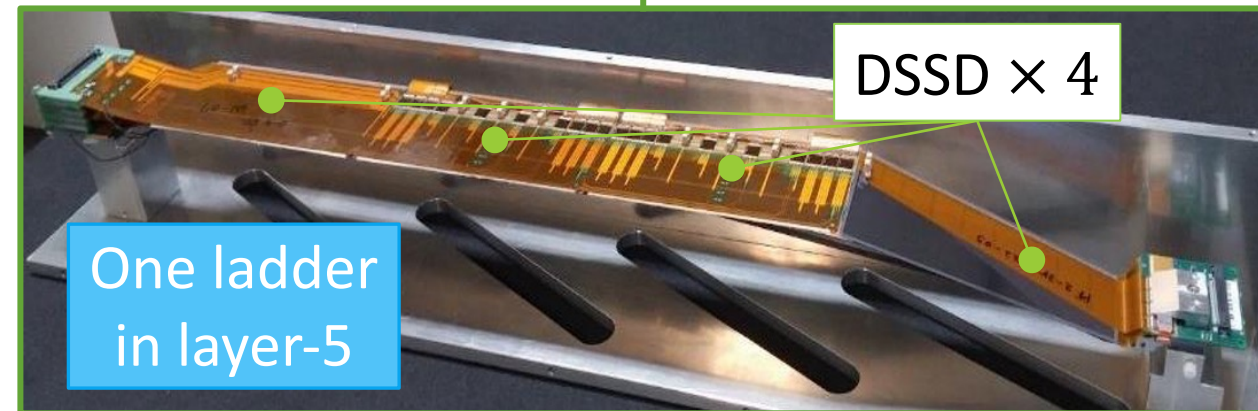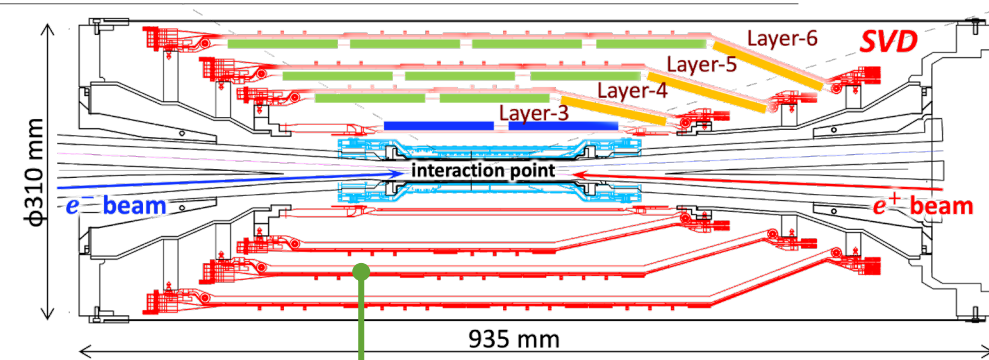◆ Layer-3-6: Silicon Vertex Detector (SVD)
- Double-sided Si strip detectors (DSSDs)
- Low material budget: 0.7% X_0 per layer

◆ SVD Roles
- Extrapolate tracks to PXD
  - essential for reconstruction of decay vertices
  - PXD region of interest for data reduction
- Stand-alone tracking for low p_T tracks
- Precise vertexing of K_S
- PID with dE/dx

◆ DSSDs
- Provide 2-D spatial information
- Strips are AC-coupled to n-type substrate
- Fully depleted at 20-60 V, operated at 100 V
- Total: 172 sensors = 1.2 m^2 sensor area = 224k readout strips

Belle II Silicon Vertex Detector (SVD)

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172 sensors
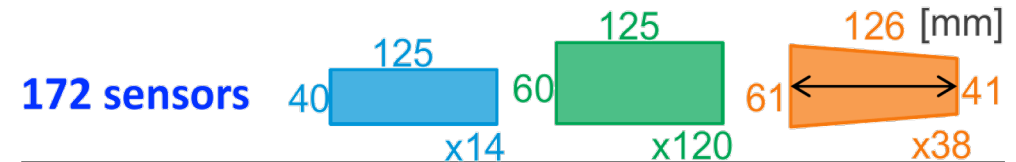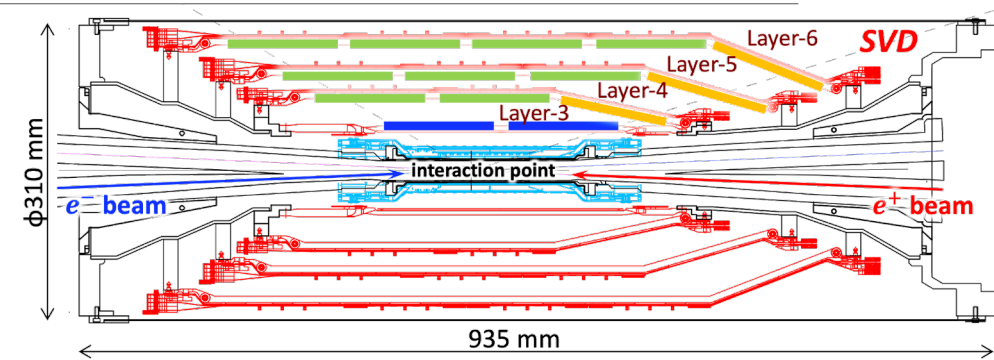
	Small	Large	Trapezoidal
# of p-strips*	768	768	768
p-strip pitch*	50 μm	75 μm	50-75 μm
# of n-strips*	768	512	512
n-strip pitch*	160 μm	240 μm	240 μm
thickness	320 μm	320 μm	300 μm
manufacturer	HPK	HPK	Micron

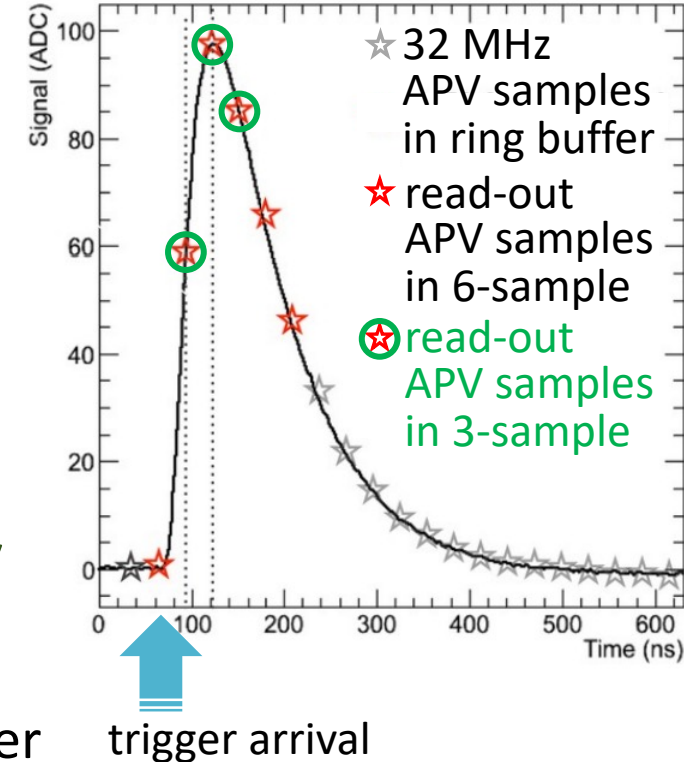*readout strips – one floating strip on both sides

Front-end ASIC: APV25

- Originally developed for CMS silicon tracker
- Fast: 50 ns shaping times
- Radiation hard: > 100 Mrad
- Power consumption: 0.4 W/chip (700 W in total)
- 128 channel inputs per chip
- Operated in "multi-peak" mode @ ~32 MHz
  - Bunch-crossing frequency ~8*32 MHz, clock not synchronous with them as in CMS
  - 6 subsequent samples read-out

- ◆ **3/6-mixed acquisition mode prepared for higher luminosity**
  - To reduce background occupancy, trigger dead-time and data-size
    - Half time-window, half FIFO usage and half hit-information in 3-sample
  - Switching sampling number according to the timing precision of trigger
  - The functionality already implemented in the real setup and confirmed to work
    - few hours of physics data-taking was smooth
  - Performance study needed before moving to 3/6-mixed mode
    - Hit efficiency is the first step → slide 16
    - To be checked: position resolution, dE/dx, hit-time

32 MHz APV samples in ring buffer

read-out APV samples in 6-sample

trigger arrival

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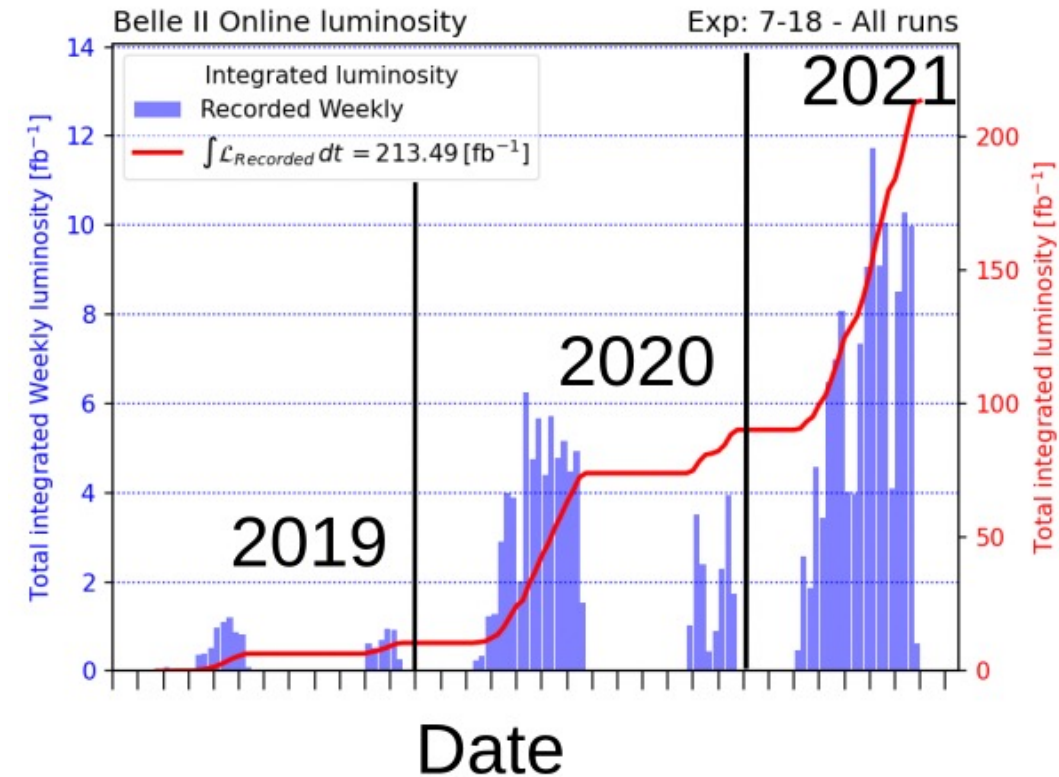
Origami chip on sensor concept

◆Readout chips directly on each middle sensor

- ■Shorter signal propagation length (smaller capacitance and noise)
- ■Thinned to 100 μm to reduce material budget
- ■Wrapped flex to read both sides from the same side
- ■Cool only one side with bi-phase −20 ℃ CO_2

Ladder in Layer-5

APV25   APV25   APV25

ORIGAMI flex
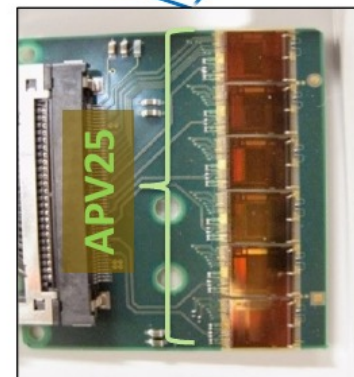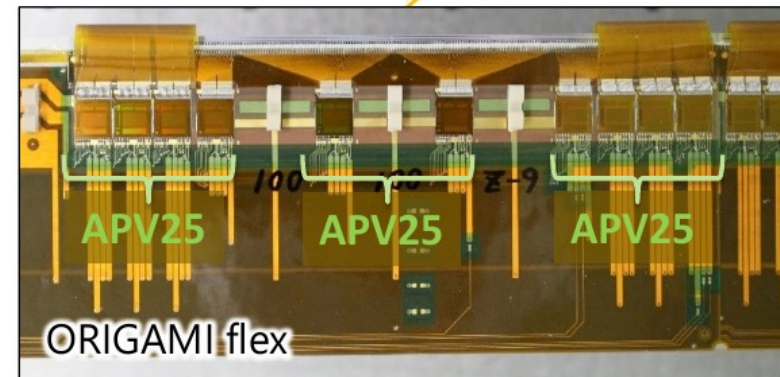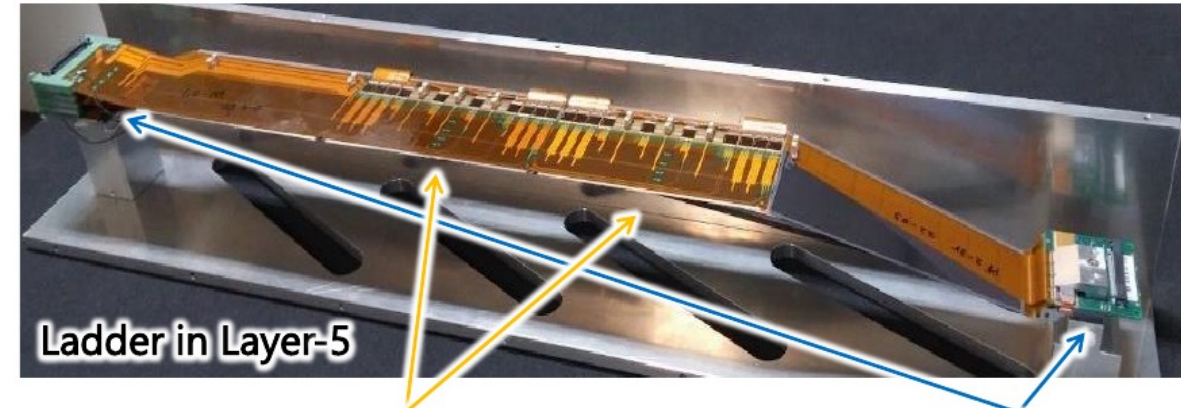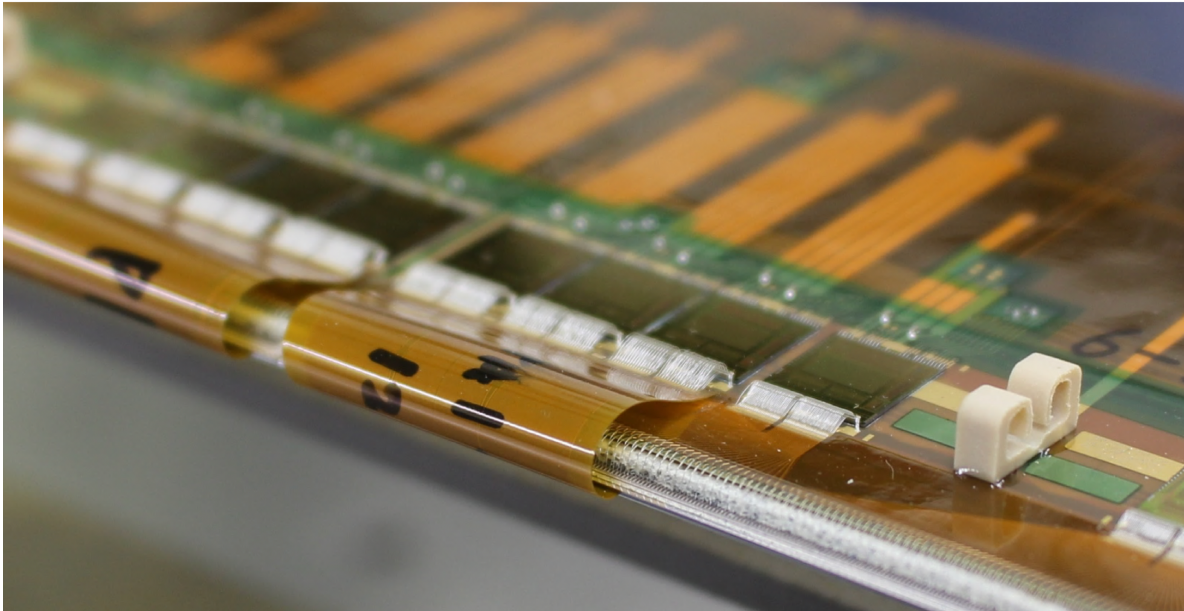
APV25

Operation & Performance

Operational experience

◆ SVD installed in 2018, operated since 2019

◆ Reliable and smooth operation without major problems
   ■ Total fraction of masked strips ~ 1%
   ■ One APV25 chip disabled in spring 2019 (out of 1748)
     → fixed by cable reconnection in summer 2019

◆ Excellent detector performance
   ● already shown at Vertex 2020
   ■ Hit efficiency stably > 99% in most of the sensors
   ■ Reasonable cluster charge distribution
     ● u/P side: agrees with MIP considering uncertainty in calibration
     ● v/N side: 10-30% due to large pitch and floating strip
   ■ Very good SNR (most probable value: 13-30)

   ■ updated simulation better agrees with data
     → *YSF talk by Mateusz Kaleta*

Belle II Online luminosity   Exp: 7-18 - All runs

Integrated luminosity
Recorded Weekly
$\int \mathcal{L}_{Recorded}\, dt = 213.49\,[fb^{-1}]$

2021
2020
2019

Total integrated Weekly luminosity [fb^{-1}]
Total integrated luminosity [fb^{-1}]
Date

Cluster position resolution → *YSF talk by Robin Leboucher*

◆ Preliminary cluster position resolution measured on e⁺e⁻ → μ⁺μ⁻ data

■ Estimated from the residual of the cluster position with respect to the track (unbiased)

- Effect of the track extrapolation error subtracted

■ Excellent position resolution in agreement with the expectations from the pitch

■ Still room for improvement for the u/P side (work ongoing)
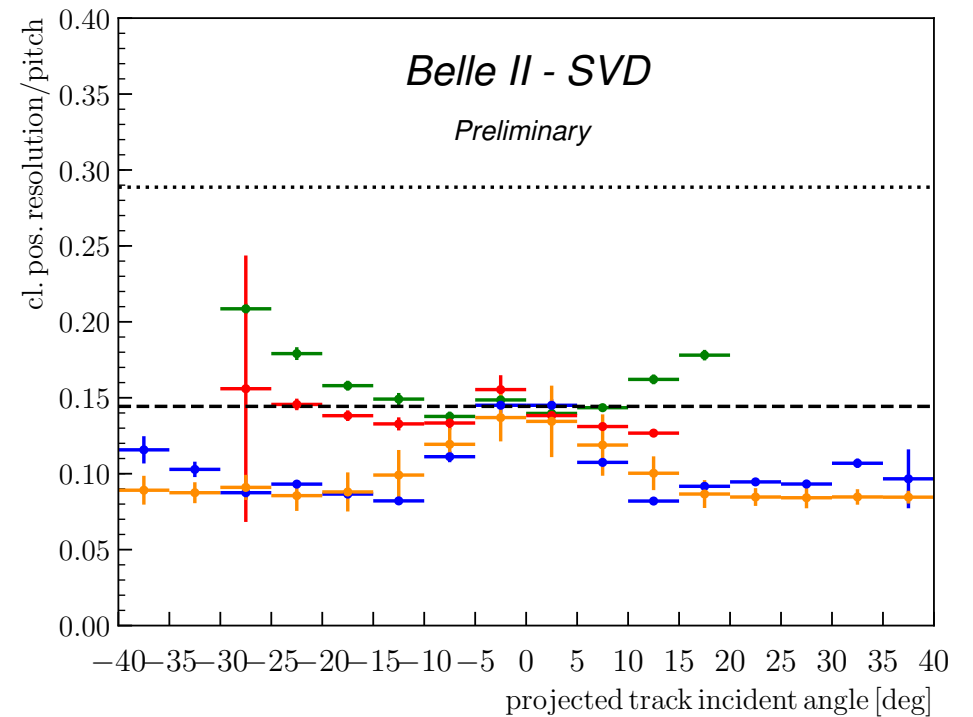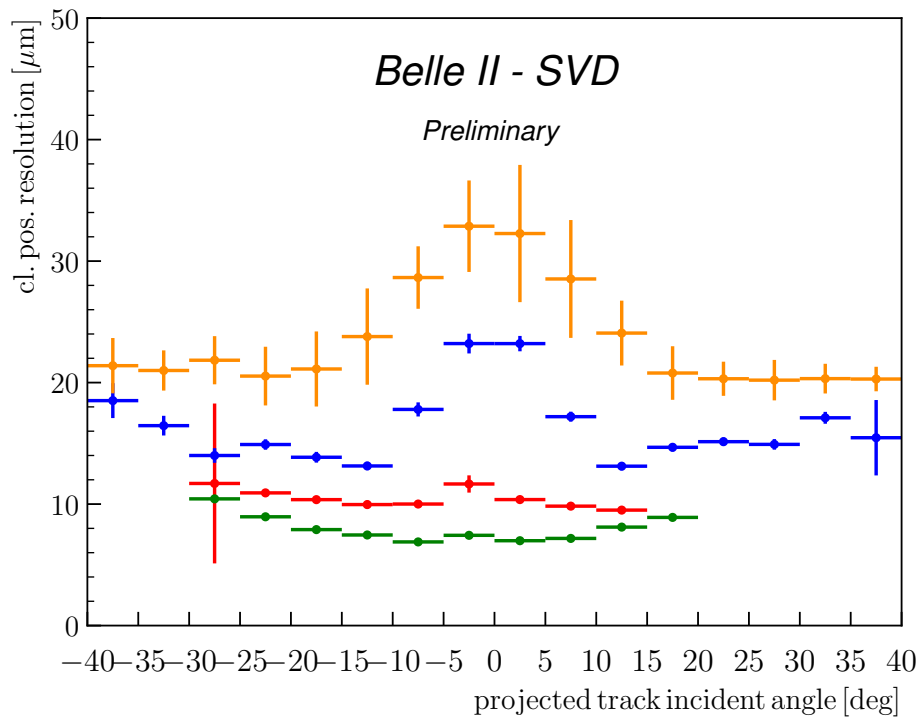
Hit-time resolution

◆ Excellent hit-time resolution with respect to event time

- Event time estimated by central drift chamber (CDC) outside of SVD
- (~ 2.9 ns u/P, ~ 2.4 ns v/N)

◆ Possible to efficiently reject off-time background hits

- Will be used for higher luminosity and background levels

N	$1.184e+05 \pm 1.331e+02$
f	0.9386 ± 0.0008
μ_1	-0.1393 ± 0.0027
σ_1	2.548 ± 0.003
μ_2	1.344 ± 0.018
σ_2	6.622 ± 0.029

Layer3, u/P side
Data: exp 10 run 3869

L3, u/P side

Belle II − SVD

SVD hit-time − CDC event time [ns]

t > -38.0 ns

sig. eff 0.99

bkg. rej 0.45

signal

Belle II - SVD

bkg

SVD hit-time [ns]

3-sample acquisition mode

◆ **Performance**

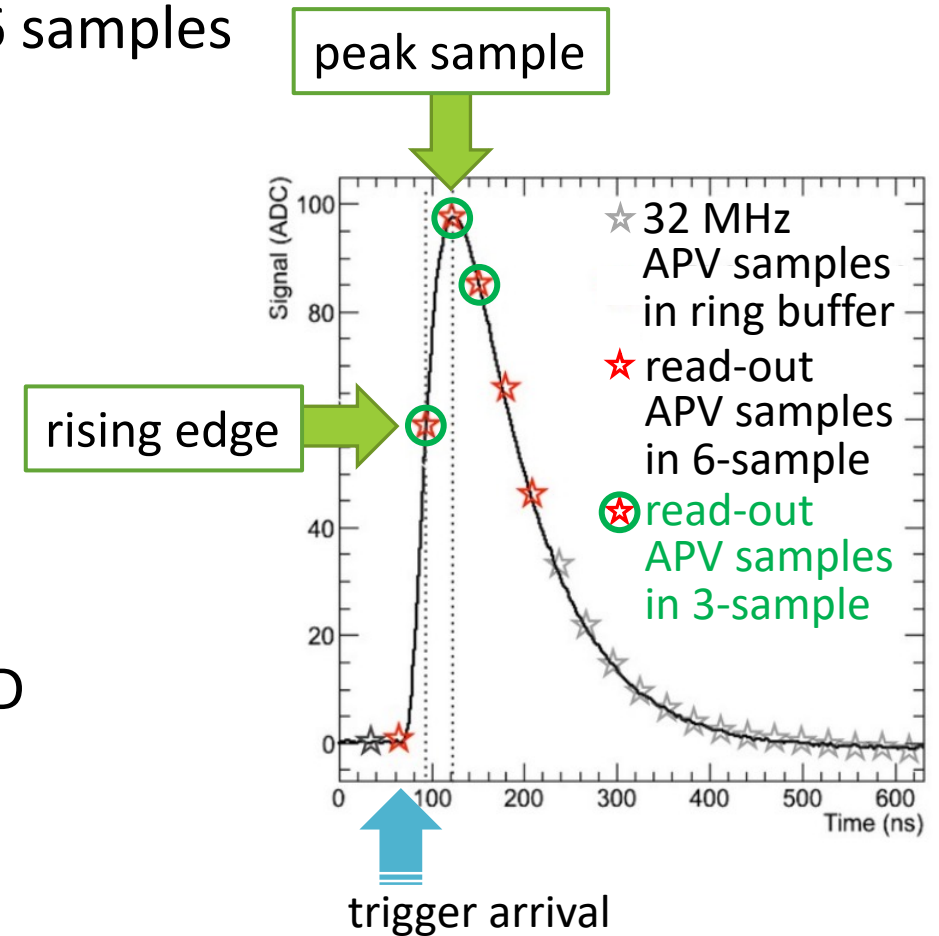■ Ideal 3 samples provide enough information as 6 samples

- amplitude – peak ADC sample
- hit-time – rising edge of the waveform

■ Degrades if the trigger timing is largely shifted

- CDC event time is a good estimator

◆ **1st step: relative hit efficiency**

■ (hit efficiency in 3-sample)/(~ in 6-sample)

■ Emulate 3-sample mode offline

■ Efficiency based on track using CDC, SVD and PXD

■ Relative efficiency > 99.9% for trigger timing shift within ±30 ns

- almost a whole clock-cycle

peak sample

rising edge

☆ 32 MHz APV samples in ring buffer

⭐ read-out APV samples in 6-sample

⭐ read-out APV samples in 3-sample

trigger arrival

3-sample acquisition mode

◆ Performance

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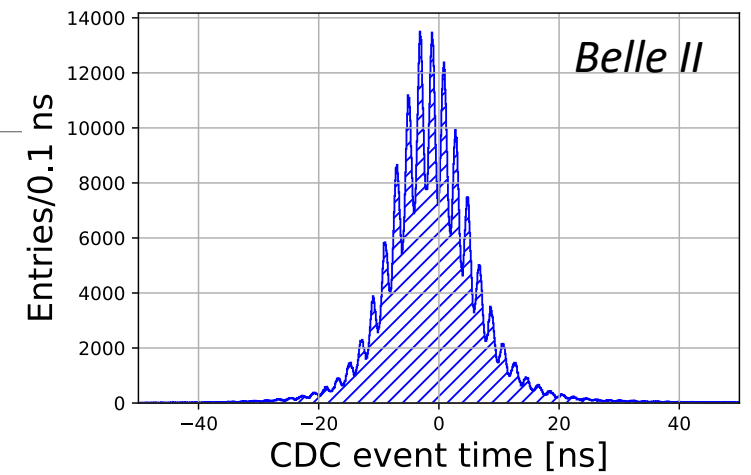
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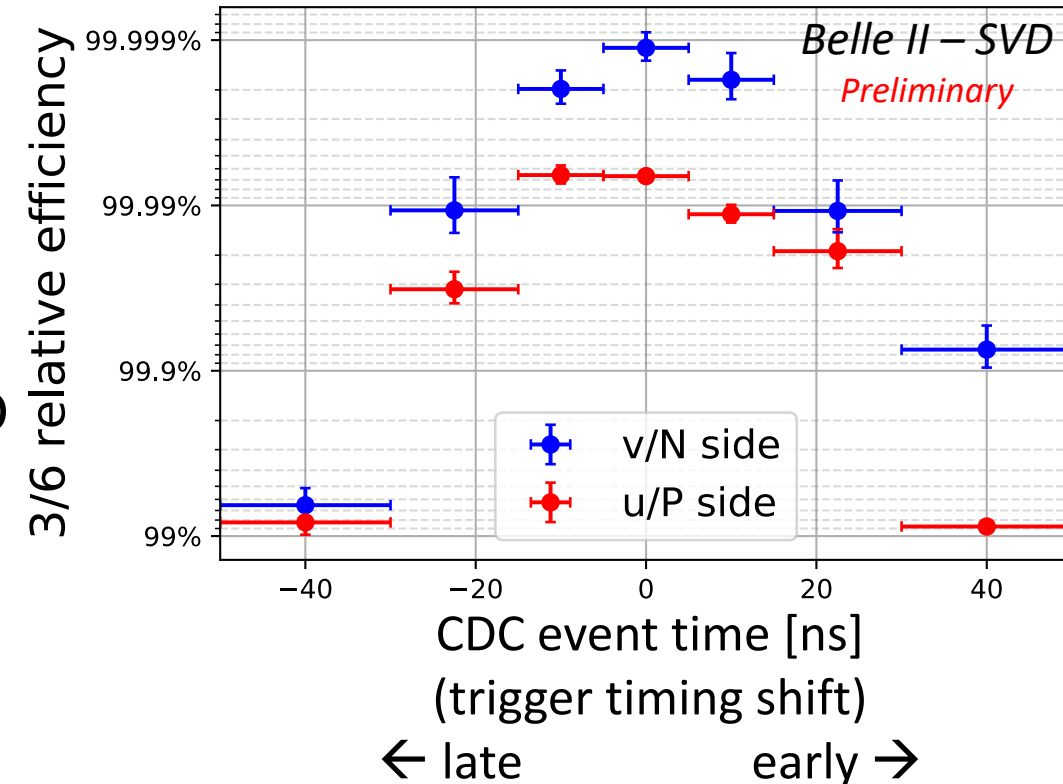
■ Emulate 3-sample mode offline

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● almost a whole clock-cycle

Belle II

all sensors combined

Belle II – SVD
Preliminary

● v/N side
● u/P side

CDC event time [ns]
(trigger timing shift)

← late   early →

Beam background & Radiation effect

Beam background and hit occupancy

◆ **Beam background increases SVD hit occupancy which degrades tracking performance**
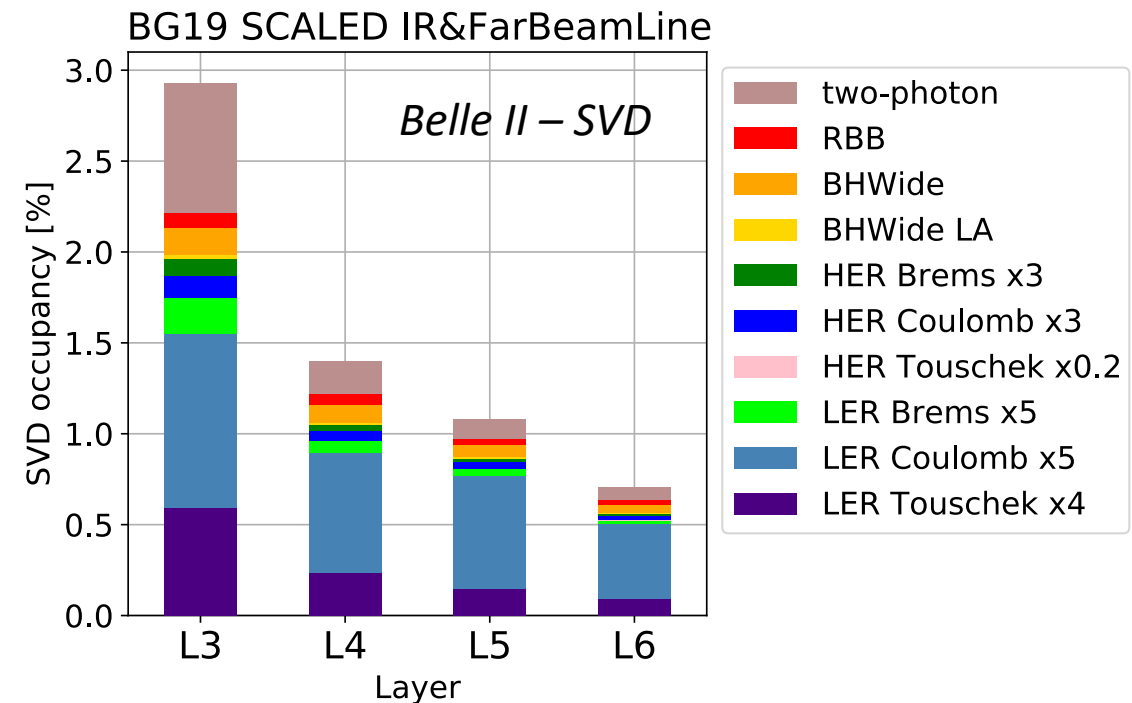
■ Present occupancy limit in layer-3: ~ 3%

- will be loosened to x~2 using hit-time to reject background

■ With current luminosity, average hit occupancy in layer-3 is well under control (< 0.5%)

■ Projection of hit occupancy at $L = 8 \times 10^{35}$ cm^{-2}s^{-1} is about 3% in layer-3

- estimated by scaling MC with data/MC ratio
- correspond to dose of ~ 0.2 Mrad/smy
  - = 1-MeV neutron fluence of ~ 5×10^{11} n$_{eq}$/cm^2/smy
  - smy: Snowmass Year = 10^7 sec
- Long term BG extrapolation affected by large uncertainties
  - optimization of collimator settings in MC
  - injection BG not included in data nor MC
  - → motivate VXD upgrade → *talk by Katsuro Nakamura*

BG19 SCALED IR&FarBeamLine

Belle II − SVD

Legend:
- two-photon
- RBB
- BHWide
- BHWide LA
- HER Brems x3
- HER Coulomb x3
- HER Touschek x0.2
- LER Brems x5
- LER Coulomb x5
- LER Touschek x4

Integrated dose

◆ SVD dose estimated by dose on diamond sensors: 70 krad in layer-3 mid plane (the most exposed to radiation)

 ■ Dose estimate based on correlation between SVD occupancy and diamonds dose

 ■ Several assumptions and large uncertainty (~ 50%)

◆ 1-MeV equivalent neutron fluence: ~ 1.6×10^{11} n_{eq}/cm^2 in first 2.5 years

 ■ assuming dose/neq fluence ratio = 2.3×10^9 $n_{eq}/cm^2/krad$ from MC

◆ analysis updated from last year

 ■ more suitable trigger used

  ● physics trigger → Poisson trigger w/o injection veto

  ● remove over estimation

Int. dose in SVD - New coeff. (from exp. 12 & 16) + EODB correction (from 14/2102)

Belle II – SVD

Preliminary

Legend:
- L3 mid plane
- L3
- L4
- L5
- L6
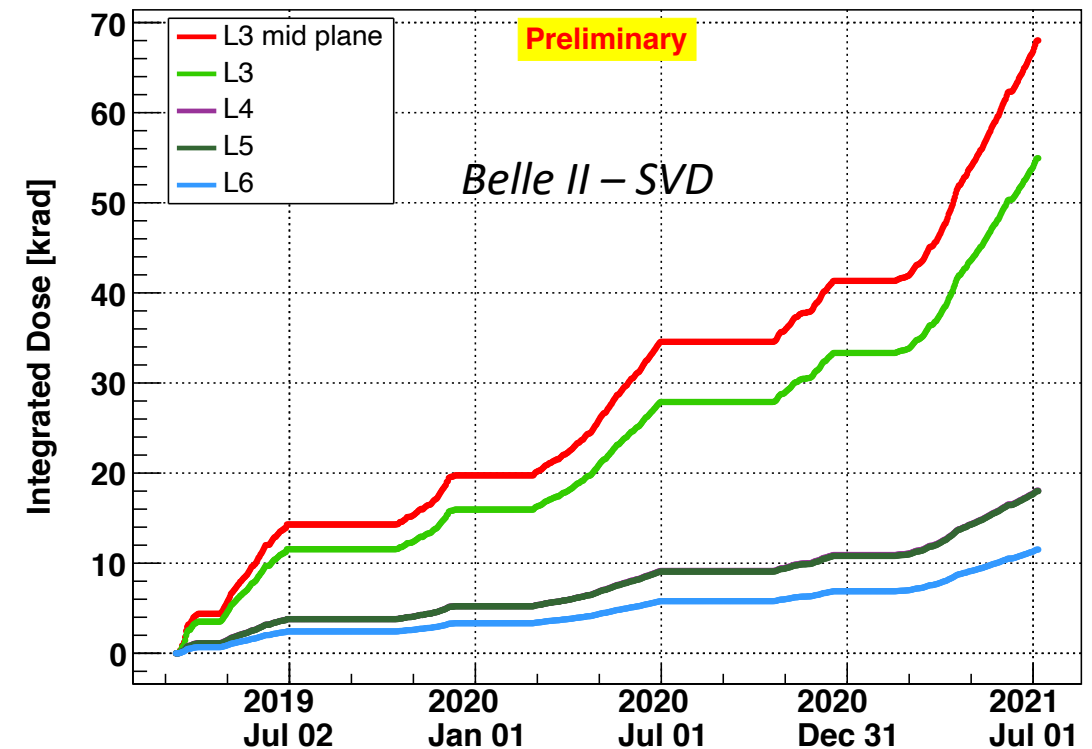
Radiation effect on leakage current

◆ **Good linear correlation between leakage current and estimated dose**

- Slope: 2-5 µA/cm²/Mrad with large variations due to temperature effects and dose spread among sensors in layer (average dose in layer used in estimate)

- Same order of magnitude as BaBar measurement (1 µA/cm²/Mrad @ 20 ℃)
  - [NIMA 729, 615-701, 2013]

- Strip noise from leakage current is suppressed by short shaping time (50ns) in APV25
  - comparable to the strip-capacitive noise only after 10Mrad irradiation → not problematic for 10 years (2 Mrad)
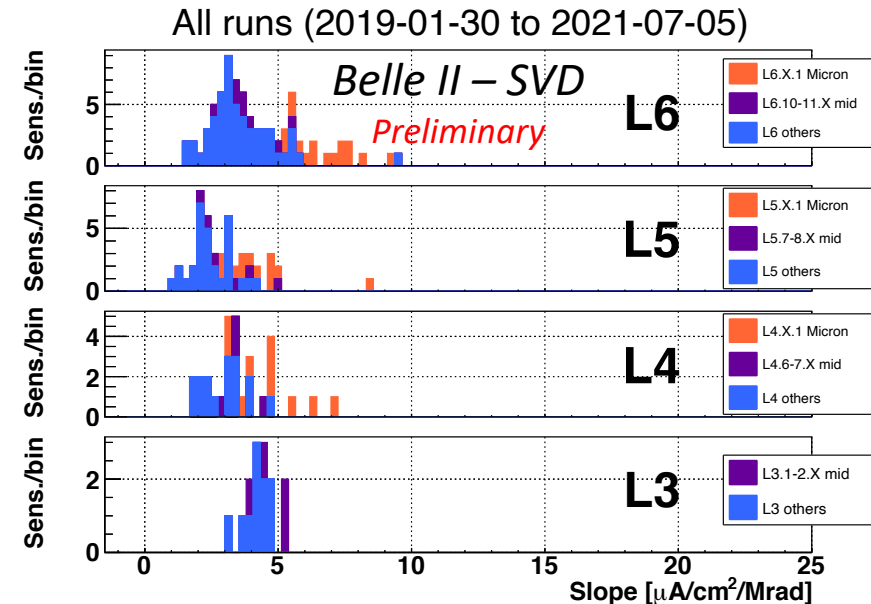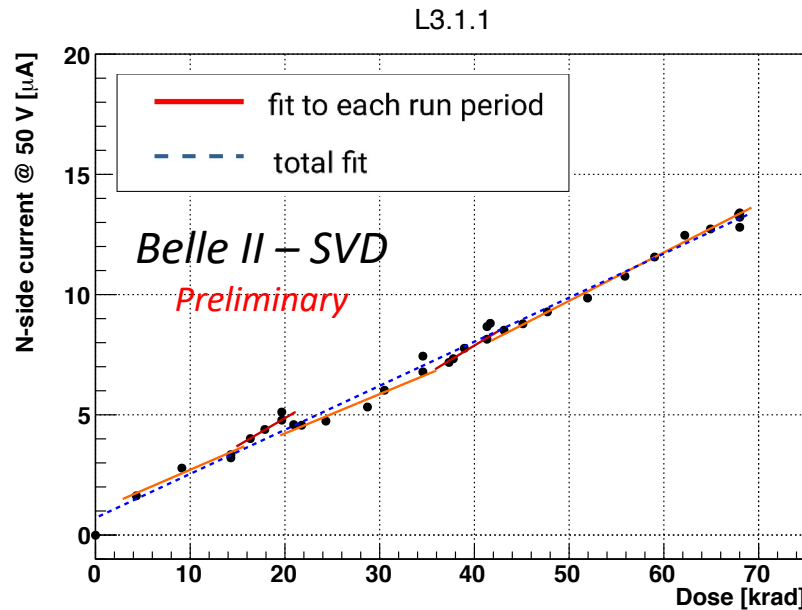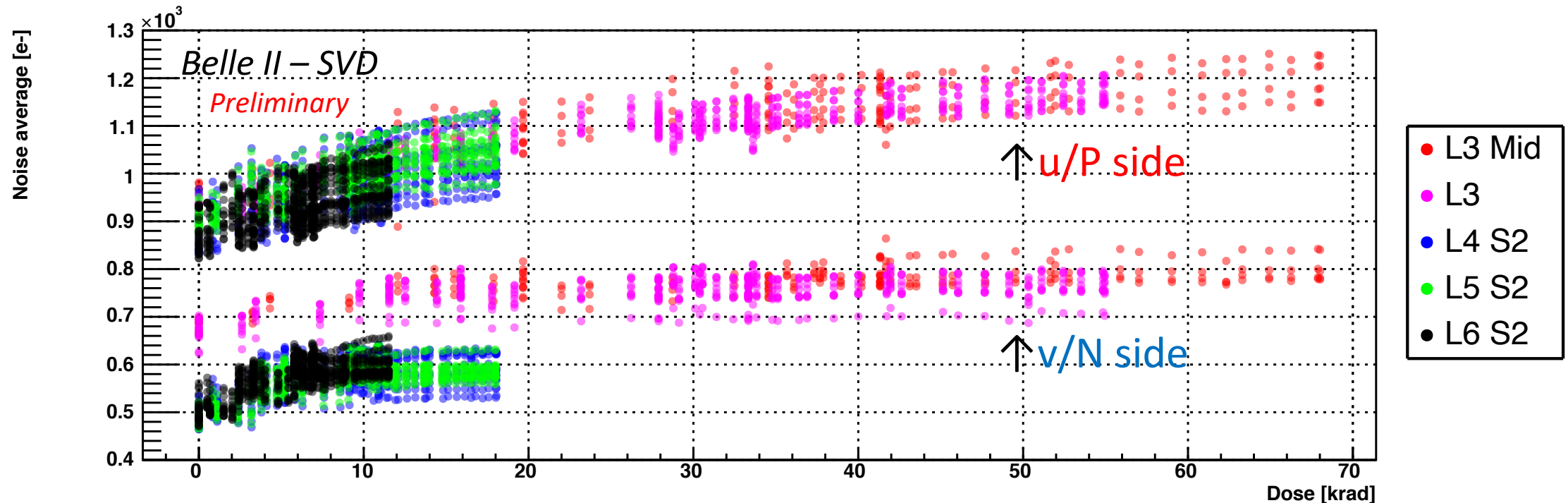
Radiation effect on strip noise

◆ **Noise increase of 20-25% in layer-3**

- Not affecting performance
- Likely due to radiation effects on sensor surface
  - Non-linear increase due to fixed oxide charges that increase inter-strip capacitance, expected to saturate
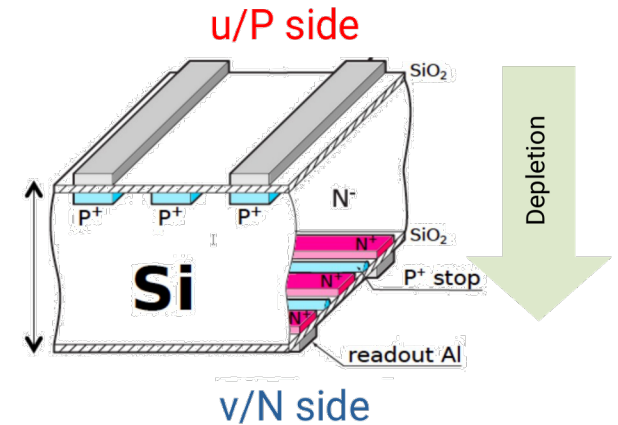- Saturation seen on v/N side and starting to be seen on u/P

Radiation effect on depletion voltage
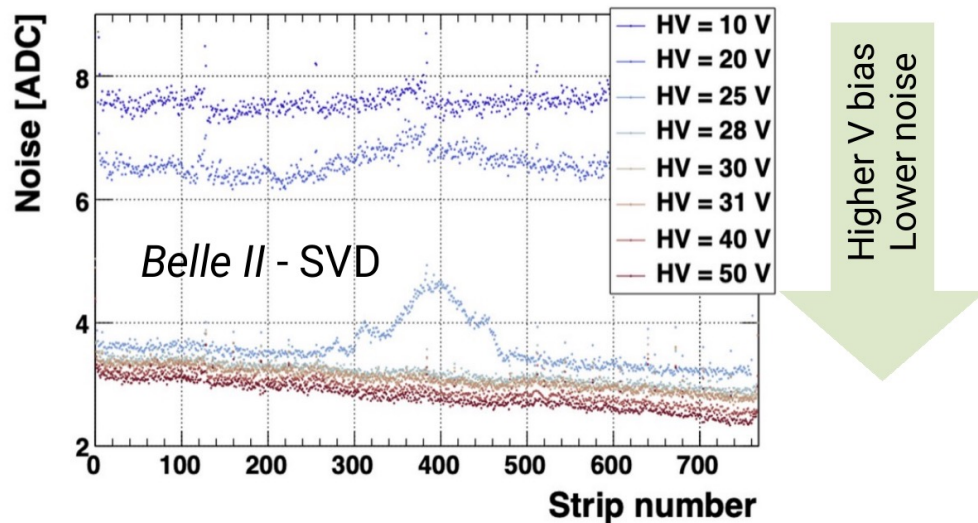
◆ **v/N side strip noise drops at full depletion**

■ v/N side insulated only when the n-type bulk is fully depleted

■ Over-depletion bias still slightly decrease noise

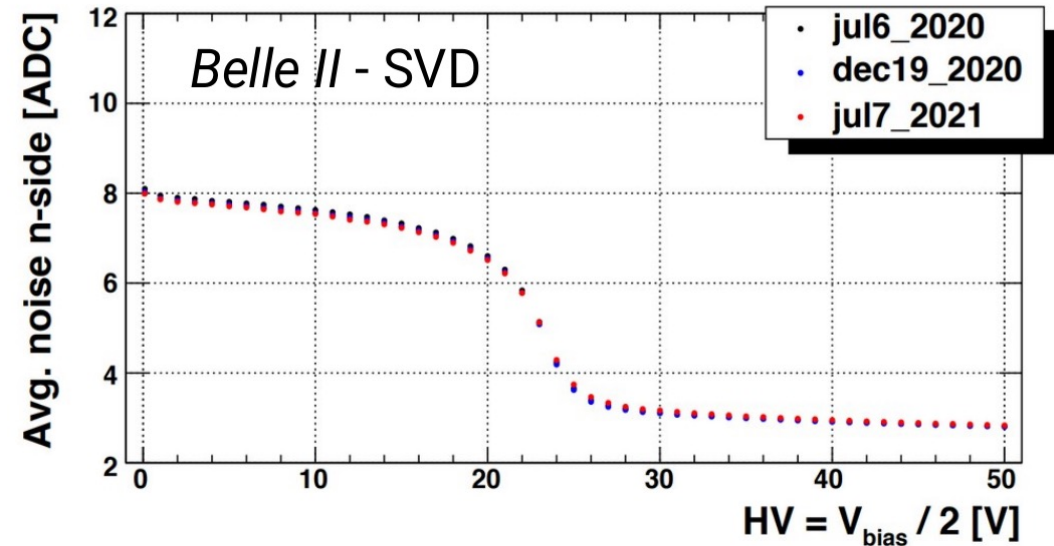● by reducing electron accumulation layer on v/N side surface

◆ **No change in full depletion voltage observed with time**

■ Consistent with low integrated neutron fluence ($\sim 1.6 \times 10^{11}$ n_{eq}/cm^2)

u/P side

Depletion

v/N side

L3.5.1 v/N Side - Strip Noise

Belle II - SVD

HV = 10 V
HV = 20 V
HV = 25 V
HV = 28 V
HV = 30 V
HV = 31 V
HV = 40 V
HV = 50 V

Higher V bias
Lower noise

L3.5.1 N Side - Noise

Belle II - SVD

jul6_2020
dec19_2020
jul7_2021

HV = V_{bias} / 2 [V]

Conclusions

◆ SVD has been taking data in Belle II since March 2019 smoothly and reliably

◆ Excellent performance in agreement with expectations
  ■ Still some room for improvement in cluster position resolution

◆ Seen first effects of radiation damage at the expected level but not affecting performance

◆ Ready to cope with increased beam background
  ■ Reject off-time background using hit-time
  ■ 3/6-mixed acquisition mode to reduce dead time, data size and occupancy

Thank you!

◆YSF talks on Belle II SVD:

■ "Measurement of the cluster position resolution of the Belle II Silicon Vertex Detector" by Robin Leboucher

■ "Simulation of the Belle II Silicon Vertex Detector" by Mateusz Kaleta

Backup

Signal charge and signal-to-noise ratio

◆ Signal charge: normalized for the track path length in silicon

- u/P side: agree with MIP considering ~ 15% uncertainty in APV25 gain calibration
- v/N side: 10-30% signal loss due to large pitch and presence of floating strip
  - similar in all sensors

◆ SNR: very good in all sensors (most probable value: 13-30)

- u/P side: larger noise due to longer strip length (larger inter-strip capacitance)
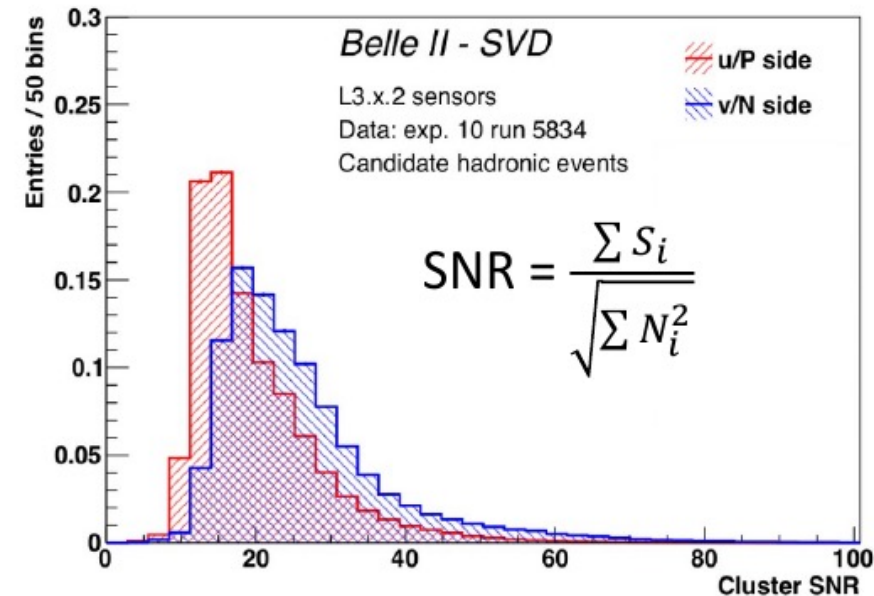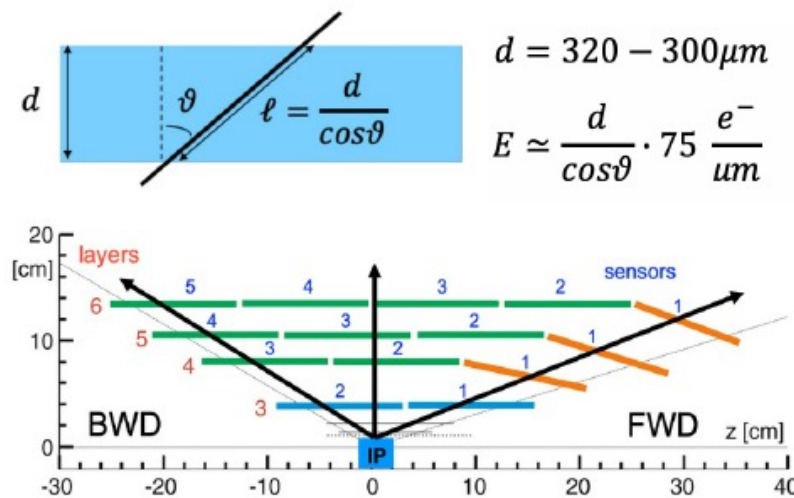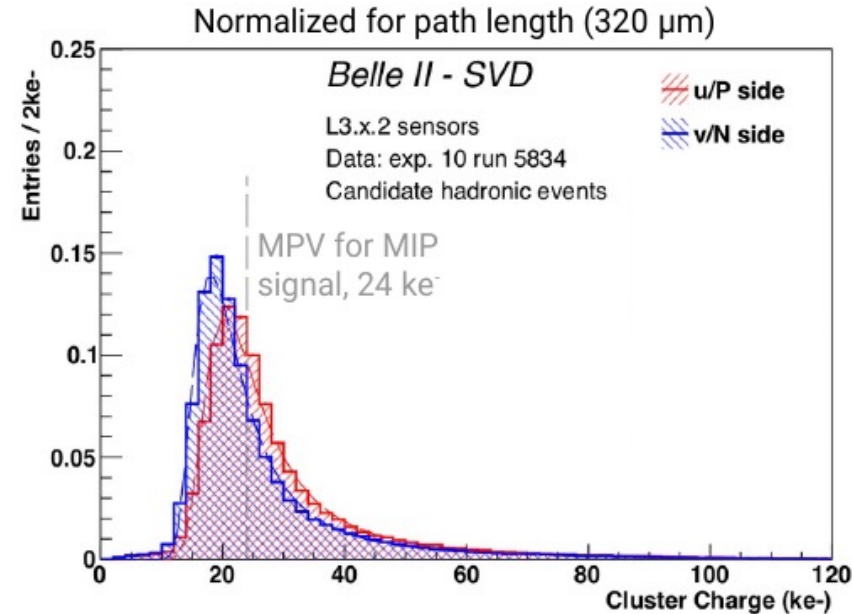
Hit-time estimation

◆ Neighboring strips over threshold are grouped into 'cluster'

◆ APV samples for strips $a_{\text{strip 0}}, a_{\text{strip 2}}, a_{\text{strip 2}}$ are summed up:

$$a_{\text{cluster } i} = \sum_{\text{strip} \in \text{cluster}} a_{\text{strip } i}$$

◆ "raw" hit-time is calculated as

$$\frac{\sum_i i \Delta t \cdot a_{\text{cluster } i}}{\sum_i a_{\text{cluster } i}},$$

where $\Delta t = 31$ ns (clock-cycle of APV25)

◆ this "raw" hit-time is calibrated to CDC event time

◆ get SVD hit-time

32 MHz APV samples in ring buffer

read-out APV samples in 6-sample

read-out APV samples in 3-sample

trigger arrival

hit-time calibration in L3.1.1 v/N

pfx_eventT0vsCoG_L3L1S1V	
Entries	78945
Mean	39.23
Mean y	−60.68
Std Dev	5.128
Std Dev y	9.388
Underflow	0
Overflow	0

CDC event time [ns] (shifted to SVD reference)

Belle II − SVD
Preliminary

raw SVD hit-time [ns?]
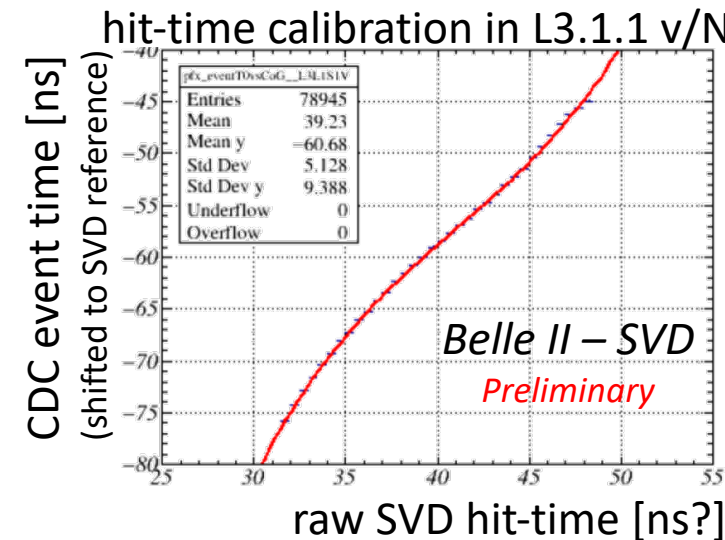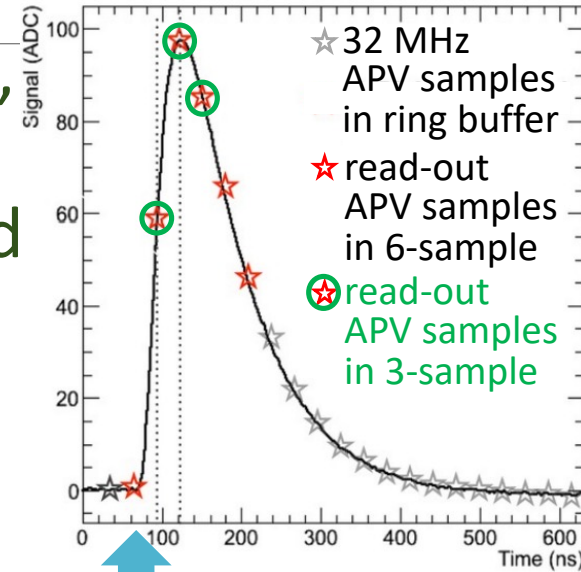
3-sample acquisition mode

◆ **efficiency**

- emulate 3-sample mode offline using trigger timing information
- based on tracks using CDC, SVD and PXD hits
- > 99.4% for trigger jitter less than 30 ns

◆ **efficiency compared to 6-sample**

- 3-sample efficiency/6-sample efficiency
- > 99.9% for trigger jitter less than 30 ns
  - almost a whole clock-cycle